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Evaluation of real-time infrared intraoperative cholangiography in a porcine model

Jack J. Liu · Mehrdad Alemozaffar · Benjamin McHone · Nadeem Dhanani · Fred Gage · Peter A. Pinto · Alexander M. Gorbach · Eric Elster

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Abstract
Background Intraoperative cholangiograms (IOCs) may increase cost, surgical time, and radiation exposure of staff and patients. The authors introduce the application of passive infrared imaging to intraoperative cholangiography as a feasible alternative to traditional fluoroscopic IOCs.
Methods A porcine model was used in which the gallbladder, cystic duct, common bile duct (CBD), and duodenum were exposed and an 18-gauge angiocatheter was inserted into the cystic duct. Infrared emission was detected using a digital infrared camera positioned 30 to 60 cm above the abdomen. Infrared images were taken in real time ($\sim$1/s) during infusion of room-temperature saline. A thermoplastic polymer stone then was inserted into the CBD. Once the artificial stone was placed, room-temperature saline was again injected. A standard single-shot renograffin IOC was obtained to confirm the obstruction. The experiment was concluded by creation of a lateral 2-mm CBD injury immediately proximal to the duodenum followed by infusion of room-temperature saline.
Results Six pigs were used in this study. Baseline infrared imaging was able to capture a visible temperature decrease, outlining the lumen of the CBD. With injection of room-temperature saline, a decrease in temperature was visualized as a dark area representing flow from the CBD to the duodenum. After placement of the synthetic stone, real-time infrared images displayed slowing of the injected bolus by the obstruction. The obstruction was correlated with fluoroscopic IOCs. Finally, after partial transection of the CBD, the infrared camera visualized saline flowing from the site of injury out into the peritoneal cavity.
Conclusions The CBD anatomy, obstruction, and injury can be clearly visualized with an infrared camera. Intraoperative infrared imaging is an emerging method already being used in several surgical fields. Ultimately, the integration of infrared and laparoscopic technology will be necessary to make infrared technology important in laparoscopic cholecystectomy.

Keywords Infrared imaging · Intraoperative cholangiogram · Laparoscopic cholecystectomy

Abbreviations

IR	infrared
IOC	intraoperative cholangiogram
RIOC	routine intraoperative cholangiogram

Jack J. Liu and Mehrdad Alemozaffar contributed equally to this work.

J. J. Liu · M. Alemozaffar · B. McHone · N. Dhanani · P. A. Pinto
Urologic Oncology Branch, National Cancer Institute, Bethesda, MD, USA
e-mail: jackjliu@gmail.com

F. Gage · E. Elster (✉)
Regenerative Medicine, Combat Casualty Care, Naval Medical Research Center, 503 Robert Grant Avenue, Suite 2W123, Silver Spring, MD 20910, USA
e-mail: elstere@nmrc.navy.mil

A. M. Gorbach
Division of Bioengineering and Physical Science, National Institute of Biomedical Imaging and Bioengineering, Bethesda, MD, USA

E. Elster
Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda, MD, USA

Laparoscopic cholecystectomy (LC) has revolutionized the way gallbladder disease is treated [1]. However, due to the limitations in visualization during laparoscopy, common bile duct (CBD) injuries have become significantly more common. The rate of CBD injuries is estimated to be 0.1% to 0.2% for open cholecystectomy and 0.2% to 1.6% for LC, a rate approximately three times greater than that for its open counterpart [2–7].

These injuries are caused most often by misidentification or misinterpretation of biliary anatomy [8]. Ludwig et al. [9] showed that operation-relevant variations in the extrahepatic biliary system occurred for 12.8% of patients undergoing LC, whereas Moossa et al. [10] showed that variations in biliary anatomy play a role in 10% to 19% of CBD injuries.

Unrecognized CBD injuries can lead to severe morbidity secondary to biliary strictures and the need for reoperation [11]. Given such serious complications, routine intraoperative cholangiograms (RIOCs) have been proposed as a means to clarify biliary anatomy and detect injuries early. With RIOCs, up to 90% of CBD injuries can be detected, whereas only 42% of injuries are detected with selective intraoperative cholangiograms (IOCs) [9]. Despite their utility, RIOCs remain controversial because they increase cost, operative time, and exposure of patients and staff to radiation [12].

To address some of these disadvantages, alternative imaging methods such as laparoscopic ultrasound (LUS) have been introduced [13]. Because LUS is less expensive, safe, and performed more quickly during surgery, its routine use may be more acceptable, with selective IOCs performed only if LUS fails. Although LUS is as effective as IOC in detecting CBD stones, its ability to visualize biliary anatomy is inferior to that of IOC [13]. In addition, LUS carries with it several disadvantages such as a steep learning curve and the need for special equipment. It also is examiner dependent [13].

An emerging method is the application of infrared imaging in the assessment of organ perfusion and anatomy. Infrared imaging can provide anatomic detail and information about tubular flow by detecting minute differences in heat between tissues. Recent advances in infrared imaging has allowed for accurate detection up to 0.01°C. Instead of radioactive contrast, cold or warm saline can be used to depict anatomy and flow through tubular structures. Thermal coronary angiography, which uses infrared technology to assess coronary artery bypass patency, is a similar technology being investigated for use in cardiothoracic surgery [14, 15].

Given the concerns associated with RIOCs and the need for effective intraoperative biliary imaging, infrared technology may be a useful addition to LC. In this study, we evaluated the ability of infrared imaging to provide useful and accurate visualization of the biliary system in a porcine model.

Methods

Infrared camera

An advanced infrared camera (Lockheed Martin IR Imaging Systems, Inc., Goleta, CA, USA) with an internally cooled infrared focal plane array detector (320 × 256 pixels) was used to capture temperature gradients across exposed tissue by passive detection of infrared emission. Infrared emission at the measured wavelength (3–5 μ) is directly proportional to temperature, and the camera has a sensitivity up to 0.02°C. It is mounted on a Zeiss operating microscope stand to provide stable positioning and mobility directly over the operative field. An electric cooling device is activated 20 min before imaging to maintain the camera's detector at an optimal operating temperature. The camera then is positioned 30 to 60 cm above the biliary system. The typical field of view includes the gallbladder, cystic duct, CBD, and duodenum, producing a spatial resolution for individual pixels of approximately 1 mm per pixel. Sequential infrared images are obtained at 1 frame per second for 250 to 600 s and digitized at 14 bits per pixel. Images are stored on a laptop computer mounted on the microscope stand and projected in real time on the operating room wall in pseudocolor.

Animal experiments

All animal procedures were approved by the Institutional Animal Care and Use Committee (UOB-006) at the National Cancer Institute. The animals were maintained in accordance with guidelines issued by the Institute of Laboratory Animal Resources, National Research Council.

Six male Yucatan pigs 7 to 8 months of age and weighing 23 to 28 kg were used for this pilot study. The pigs were maintained under general anesthesia using 1% isoflurane.

Once adequate anesthesia was established, a midline laparotomy was performed followed by isolation of the gallbladder, cystic duct, and cystic artery. A cholecystotomy was created, from which bile was evacuated, and an 18-gauge angiocatheter was inserted into the gallbladder then secured in position.

Baseline images of the gallbladder, cystic duct, CBD, and duodenum were obtained. Room-temperature (22°C) or warm (37°C) saline contrast then was injected into the gallbladder via an 18-gauge angiocatheter, and infrared images were acquired during infusion. Next, a cholecystectomy was performed, and the cystic duct was cannulated

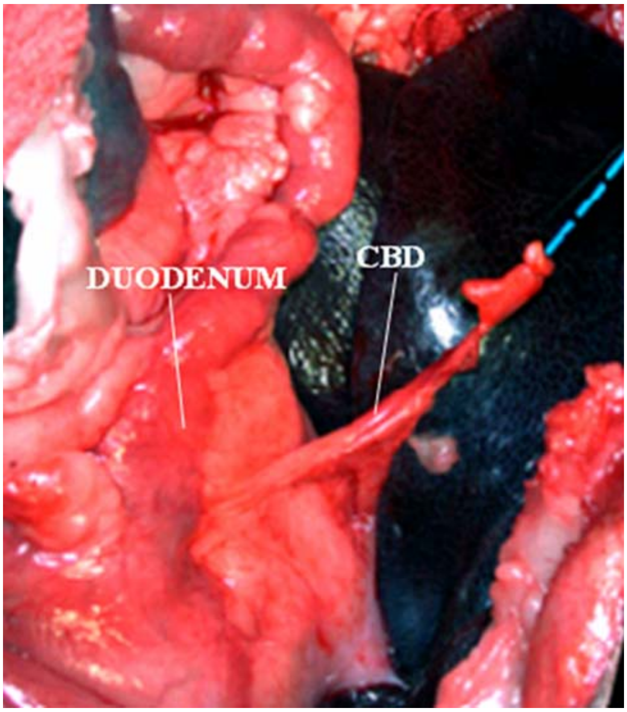

Fig. 1 Visible light image of the general surgical field after cholecystectomy and placement of a catheter through the cystic duct.

with an 18-gauge angiocatheter (Fig. 1). Saline contrast was infused again, but via the cystic duct, while infrared images were captured.

An obstruction then was introduced using a 1-cm synthetic thermoplastic polymer stone. The synthetic stone was passed in a retrograde manner through the ampulla and into the CBD via a duodenostomy. Saline contrast was infused into the angiocatheter while infrared images were captured. The obstruction was confirmed by performing a single-shot renograffin IOC.

Next, an injury was created by a 2-mm transverse laceration to the CBD 2 cm above the duodenum. Saline contrast was again infused into the cystic duct, and infrared images were captured.

Infrared image evaluation

A series of nine randomized infrared images were presented to two surgeons at the National Naval Medical Center for blinded evaluation. The series comprised three images of normal anatomy, three images of CBD obstruction, and three images of a CBD injury. Neither surgeon had ever used infrared imaging. Therefore, sample infrared pictures of normal biliary anatomy, CBD obstruction, and CBD injury were shown to each evaluator. The reviewers then evaluated each image on four parameters: ability to visualize CBD, duodenal anatomy, filling defect, and leakage of contrast. In addition, comments from the reviewers were elicited for each of the images.

Results

Infrared imaging was successfully performed for all six animals. The baseline infrared images were capable of visualizing biliary structures even before the injection of saline contrast.

With infrared imaging, the lumens of the CBD and duodenum can be visualized as areas of lower infrared intensity surrounded by areas of higher infrared intensity representing surrounding tissue (Fig. 2a). After injection of room-temperature saline into the CBD, an area of low infrared intensity can be seen extending unimpeded through the biliary system highlighting the anatomy of the CBD and the duodenum (Fig. 2b). The area may appear larger than the actual luminal size due to cooling of the areas immediately outside the CBD and duodenum.

Proximal anatomy also may be visualized, as demonstrated in Fig. 2c. Using warm saline contrast, the hepatic ducts together with the CBD and duodenum can be visualized as areas of increased infrared intensity.

Both the infrared camera and renograffin IOCs were able to demonstrate an obstruction in the CBD. Unlike the previous images, these showed no evidence of flow into the duodenum after injection of room-temperature saline (Fig. 3a). Instead, we could see an area of low infrared intensity just distal to the angiocatheter that stopped abruptly in the CBD. The renograffin IOC confirmed the obstruction. It was illustrated by a radio-opaque area that stopped abruptly at the site of obstruction (Figs. 3b and 4).

A 2-mm injury was successfully created for all six animals. Infrared imaging was able to demonstrate the injury by visualizing an extravasation of infused room-temperature saline into the operative field. This leakage was represented by a general area of low infrared emission (Fig. 4).

Two surgeons presented with randomized infrared images were able to identify all images demonstrating normal anatomy. However, they were unable to identify the duodenum in two of the three images. Both were able to identify filling defects and leakage of contrast in two of the three images. The surgeons commented that the images they could not identify correctly, either anatomically (the duodenum) or pathologically, were difficult to interpret and would require further study.

Discussion

Since the introduction of LC, there have been many efforts to reduce the rate of CBD injury. Standard principles and

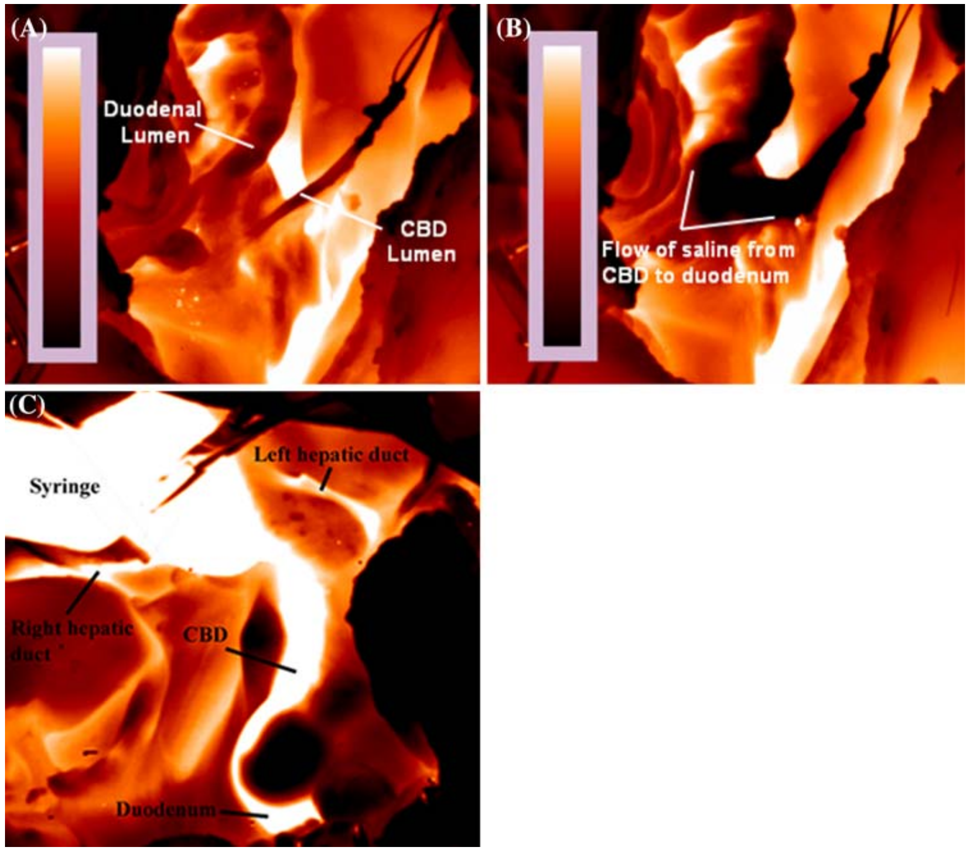

Fig. 2 Corresponding infrared imaging of the common bile duct (CBD) and duodenum after cholecystectomy. (**a**) View of the biliary system before room-temperature saline infusion. (**b**) View after injection of room-temperature saline into the CBD. Saline can be seen flowing unimpeded from the CBD into the duodenum. (**c**) Warm saline contrast demonstrating proximal and distal biliary anatomy

IOCs have been introduced to prevent such injuries [16]. The benefits of RIOCs have been studied extensively and have shown promising results in the reduction of CBD injuries. Despite these potential benefits, no consensus exists to date regarding the routine use of IOCs because of increased cost, surgical time, and radiation exposure. Alternative imaging methods such as LUS also have been considered for addressing some drawbacks of radio contrast IOCs. However, their accuracy and feasibility are controversial [13].

Infrared imaging technology may be a feasible alternative for addressing many drawbacks of traditional RIOCs. Using real-time infrared assessment, we were able to demonstrate biliary anatomy, obstruction, and injury clearly.

Due to the drawbacks of RIOCs, the majority of surgeons use them only selectively. Typically, IOCs are used only when the suspicion for injury is high or clinical or radiographic signs suggest the presence of a CBD stone. Besides the problems with increased operative time, cost, and radiation exposure, there are several additional concerns about IOCs that prevent the routine use of RIOCs. Opponents of RIOCs also are concerned about iatrogenic injury caused by mistaken cannulation of the CBD [17]. There is further concern about unnecessary exploration of the biliary system because the sensitivity of IOCs for CBD stones is not well established [18].

Our results demonstrate that infrared imaging may be both a feasible and useful application to intraoperative imaging and may have several advantages over traditional IOCs. As our images illustrate, infrared imaging has the sensitivity to distinguish luminal and solid structures even without contrast. When saline contrast is used, the course of the CBD is clearly demonstrated.

We successfully demonstrated the presence of a CBD obstruction, which was confirmed by a single-shot renografin IOC. Biliary injury also was visualized easily as an extravasation of saline contrast. Using blinded evaluation, we demonstrated that surgeons new to the imaging method can identify important structures and pathology. Although unfamiliarity with the technology, poor orientation of images, and the lack of real-time feedback may have contributed to the evaluators' inability to identify all the images correctly, they were able to distinguish these as difficult-to-interpret images requiring further study. This suggests that infrared imaging may provide a useful screening tool to be followed by standard fluoroscopic imaging in questionable cases or instances of pathology.

Infrared imaging has the potential to address many drawbacks of fluoroscopic IOCs. With saline used as contrast, there is no concern about excess radiation exposure. The room-temperature saline also quickly

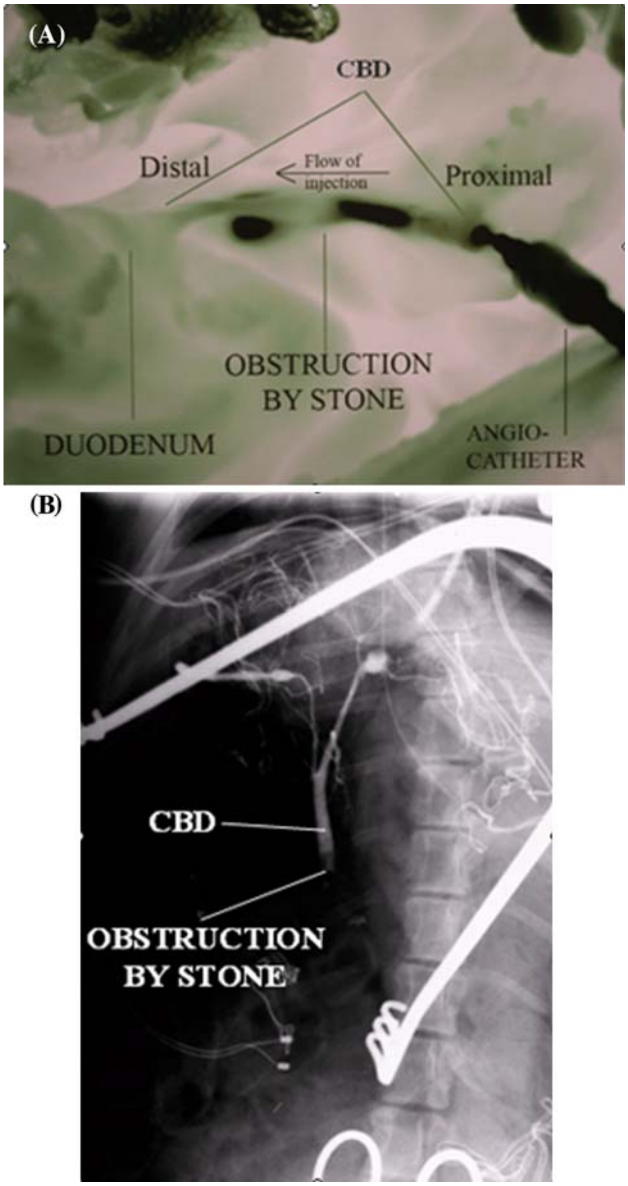

Fig. 3 Infrared and single-shot renograffin intraoperative cholangiogram (IOC) of a common bile duct (CBD) obstruction created by a synthetic stone. (**a**) Infrared image with black and white color scheme demonstrating an impedance to contrast flow. (**b**) A renograffin IOC confirms the successful obstruction

equilibrates to the surrounding temperature, which allows for convenient repeat imaging of the biliary system. Additionally, we were able to image the CBD by injecting saline contrast via a cholecystomy. This is important because CBD injuries are another concern with IOCs.

To address the problems of surgical time and cost associated with RIOCs, we currently are developing a laparoscopic camera that will have the capability of alternating between visible and infrared spectra. This camera would allow for rapid acquisition of IOCs without the need for additional staff or equipment. We also are collaborating to develop an algorithm for fusing infrared and visible images to provide an integrated display [19].

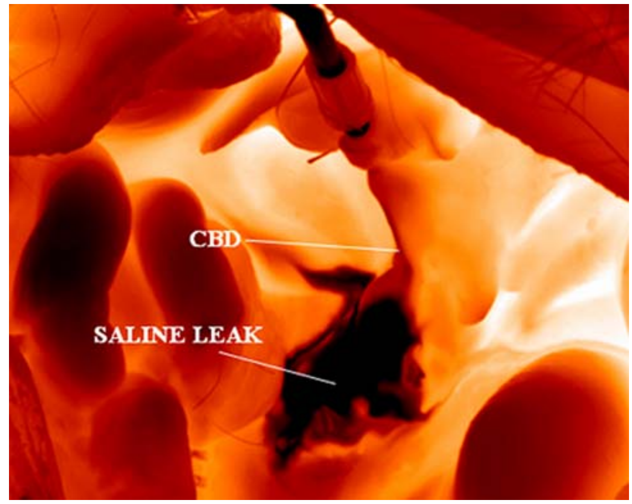

Fig. 4 Infrared image of the biliary system after a 2-mm injury to the common bile duct (CBD). Extravasation of room-temperature saline is demonstrated by the low-intensity area surrounding the CBD

Another important advantage of infrared imaging is that the images are acquired in real time. This can provide surgeons with constant anatomic information that can adapt to the changing operative field and may even help decrease operative time.

Although RIOCs may have many disadvantages, their benefits in LC have been well documented and studied. We have shown that infrared imaging may have the potential to address the issues regarding surgical time, cost, and radiation exposure associated with RIOCs. Coupled with the development of a laparoscopic infrared camera and an algorithm for image fusion, this technology may play a significant role in the future implementation of RIOCs. However, these results are preliminary, and we cannot accurately predict the sensitivity and practicality of this technology. Clearly, this method will need to be studied in a clinical model that contrasts standard fluoroscopic IOC with infrared IOC for further development of these promising results.

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References

1. NIH Consensus Development Panel on Gallstones and Laparoscopic Cholecystectomy (1993) Gallstones and laparoscopic cholecystectomy. Surg Endosc 7:271–279
2. Adamsen S, Hansen OH, Funch-Jensen P, Schulze S, Stage JG, Wara P (1997) Bile duct injury during laparoscopic cholecystectomy: a prospective nationwide series. J Am Coll Surg 184:571–578
3. Berci G (1998) Complications of laparoscopic cholecystectomy. Surg Endosc 12:291–293
4. Davidoff AM, Pappas TN, Murray EA, Hilleren DJ, Johnson RD, Baker ME, Newman GE, Cotton PB, Meyers WC (1992) Mechanisms of major biliary injury during laparoscopic cholecystectomy. Ann Surg 215:196–215
5. Deziel DJ, Millikan KW, Staren ED, Doolas A, Economou SG (1993) The impact of laparoscopic cholecystectomy on the operative experience of surgical residents. Surg Endosc 7:17–21
6. Gigot J, Etienne J, Aerts R, Wibin E, Dallemagne B, Deweer F, Fortunati D, Legrand M, Vereecken L, Doumont J, Van Reepinghen P, Beguin C (1997) The dramatic reality of biliary tract injury during laparoscopic cholecystectomy: an anonymous multicenter Belgian survey of 65 patients. Surg Endosc 11(12):1171–1178
7. Regoly-Merei J, Ihasz M, Szeberin Z, Sandor J, Mate M (1998) Biliary tract complications in laparoscopic cholecystectomy: a multicenter study of 148 biliary tract injuries in 26,440 operations. Surg Endosc 12:294–300
8. Olsen D (1997) Bile duct injuries during laparoscopic cholecystectomy. Surg Endosc 11:133–138
9. Ludwig K, Bernhardt J, Lorenz D (2002) Value and consequences of routine intraoperative cholangiography during cholecystectomy. Surg Laparosc Endosc Percutan Tech 12:154–159
10. Moossa AR, Easter DW, Van SE, Casola G, D'Agostino H (1992) Laparoscopic injuries to the bile duct: a cause for concern. Ann Surg 215:203–208
11. Ostroff J, LaBerge JM (2006) Endoscopic and radiologic treatment of biliary disease. In: Feldman M, Friedman LS, Brandt LJ et al (eds) Feldman: Sleisenger & Fordtran's gastrointestinal and liver disease. 8th ed. Saunders Elsevier, Philadelphia, PA pp 1503–1535
12. Piacentini F, Perri S, Pietrangeli F, Nardi M Jr, Dalla TA, Nicita A, Lotti R, Castaldo P, Gabbrielli F, Castiglia D, Citone D (2003) Intraoperative cholangiography during laparoscopic cholecystectomy: selective or routine? G Chir 24(4):123–128
13. Machi J, Oishi AJ, Tajiri T, Murayama KM, Furumoto NL, Oishi RH (2007) Routine laparoscopic ultrasound can significantly reduce the need for selective intraoperative cholangiography during cholecystectomy. Surg Endosc 21:270–274
14. Garbade J, Ullmann C, Hollenstein M, Barten MJ, Jacobs S, Dhein S, Walther T, Gummert JF, Falk V, Mohr FW (2006) Modeling of temperature mapping for quantitative dynamic infrared coronary angiography for intraoperative graft patency control. J Thorac Cardiovasc Surg 131:1344–1351
15. Sonmez B, Arbatli H, Tansal S, Yagan N, Unal M, Demirsoy E, Tukenmez F, Yilmaz O (2003) Real-time patency control with thermal coronary angiography in 1,401 coronary artery bypass grafting patients. Eur J Cardiothorac Surg 24:961–966
16. Stewart L, Way LW (1995) Bile duct injuries during laparoscopic cholecystectomy: factors that influence the results of treatment. Arch Surg 130:1123–1128
17. Strasberg SM, Eagon CJ, Drebin JA (2000) The "hidden cystic duct" syndrome and the infundibular technique of laparoscopic cholecystectomy: the danger of the false infundibulum. J Am Coll Surg 191:661–667
18. Nickkholgh A, Soltaniyekta S, Kalbasi H (2006) Routine versus selective intraoperative cholangiography during laparoscopic cholecystectomy: a survey of 2,130 patients undergoing laparoscopic cholecystectomy. Surg Endosc 20:868–874
19. Hana B, Gorbach A, Silva J, Gilfillan L, Kirk A, Elster E. Intraoperative assessment of critical biliary structures with visible range/infrared image fusion. J Am Coll Surg, Accepted for publication